Methods for Passive Optical Detection and Relative Navigation for Rendezvous with a Non-Cooperative Object at Mars

AAS 18-288
2018 AAS Astrodynamics Specialist Conference, Snowbird, UT
August 20th, 2018

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The information presented about potential Mars sample return architectures is provided for planning and discussion purposes only. NASA has made no official decision to implement Mars sample return.

Potential Mars Sample Return Architecture

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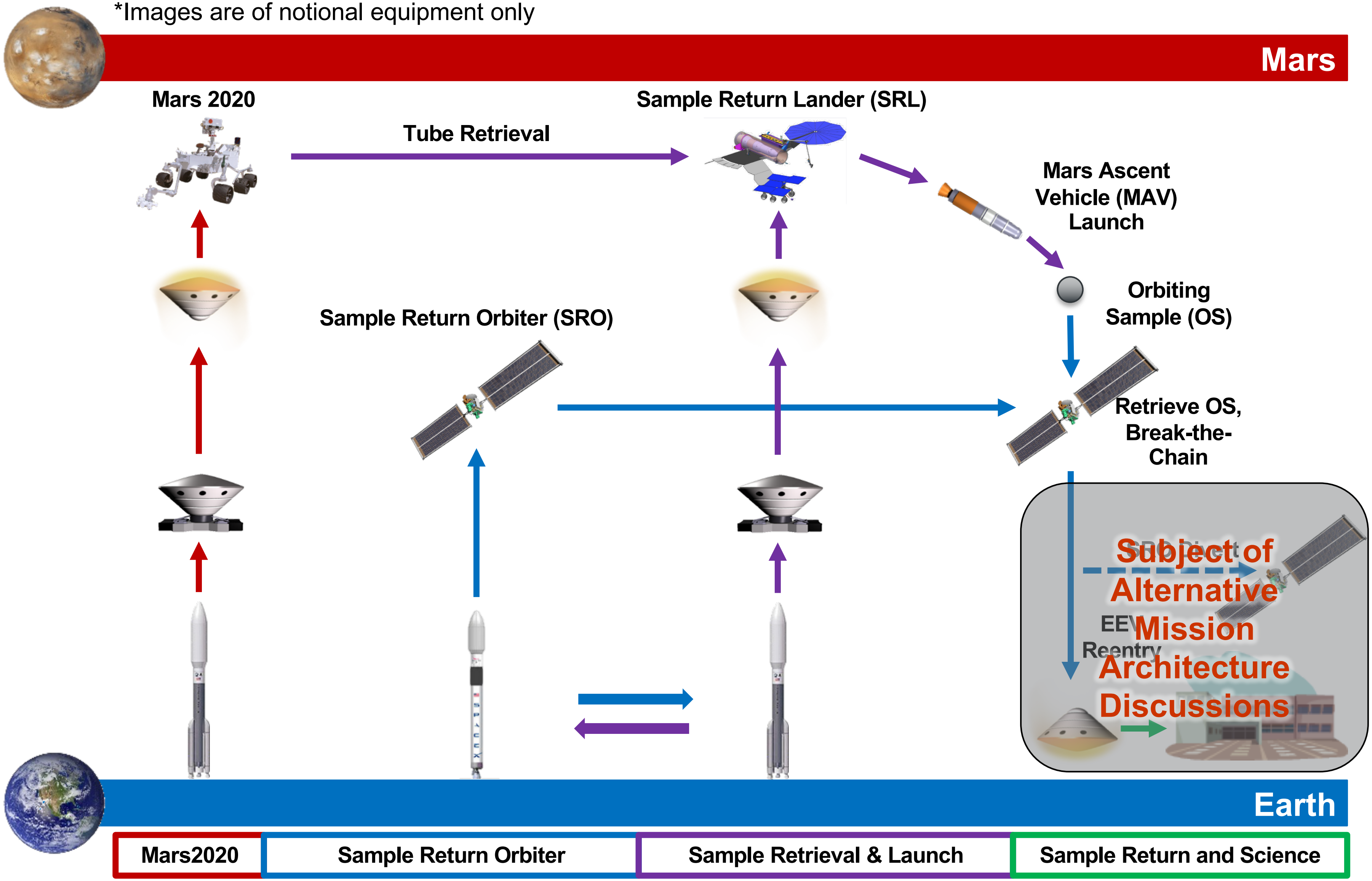
*Images are of notional equipment only



Notional Problem Statement

- The Sample Return Orbiter (SRO) arrives in martian orbit by any of several means:
  - Solar Electric Propulsion (SEP) rendezvous w/spiral
  - Chemical Propulsion (CP) insertion w/aerobraking
  - A hybrid SEP/CP scheme w/staging
- The Sample Return Lander (SRL) would have already landed and would be completing its mission:
  - Land, deploy fetch rover to collect sample tubes
  - Deposit sample tubes in an Orbiting Sample (OS) container mounted in a Mars Ascent Vehicle (MAV)
  - Launch MAV w/OS to Low Mars Orbit (LMO)
- The SRO must detect and rendezvous with the OS in a way that maximizes failure tolerance.

Example Solution

- The notional SRO would make use of optical cameras to acquire and determine the orbital elements of the OS.
- Camera suite:
  - Long-range detection, initial navigation:
    - Narrow Angle Camera (NAC) x1
  - Redundant detection, stereo navigation:
    - Medium Angle Camera (MAC) x1
  - Stereo terminal rendezvous, OS inspection:
    - Wide Angle Camera (WAC) x3
- Initial acquisition imagery would be downlinked and processed on Earth to generate orbit matching maneuvers.
- Terminal rendezvous would be performed autonomously with key go/no-go points for ground authorization.

Rendezvous with a SEP Orbiter

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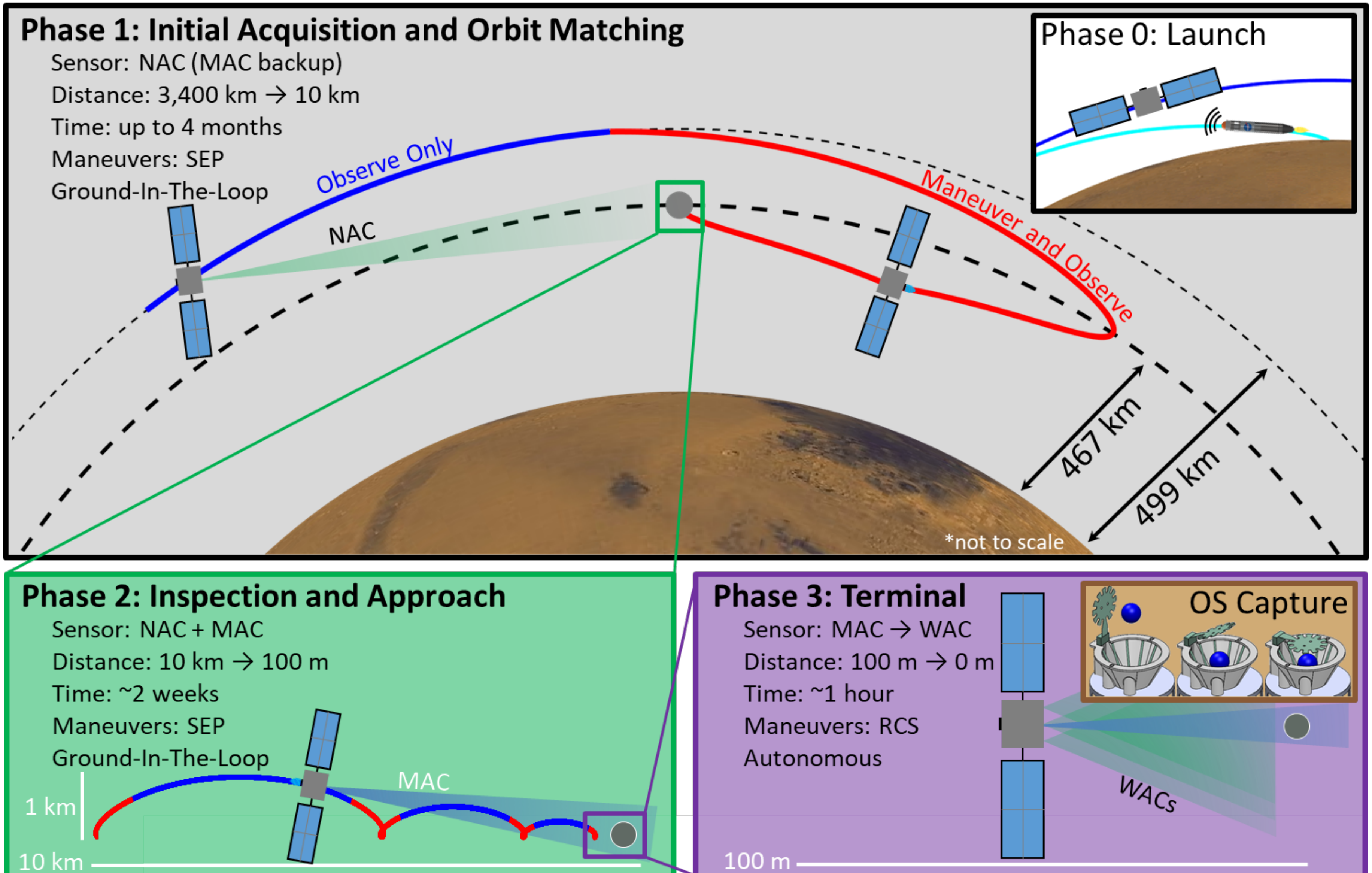

Outline

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- Introduction/problem statement
- Development of a new SNR equation
- Requirements for an example camera suite
- OS orbit insertion dispersions
- Relative orbital dynamics, simulation
- Radiometric results in the presence of dynamics
- SNR results vs. simulation time
- Relative navigation
- Extension to terminal rendezvous
- Conclusion
- References

The SNR Equation

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*Variables all described in paper

- Detection begins with signal-to-noise-ratio (SNR) equation.
- Previous version (Woolley et al. 2011) gives relevant SNR in terms of camera parameters, OS parameters, and geometry:

$$SNR = \frac{\pi d_{ap}^2}{4} f t_e * \left(\frac{\pi d_{OS}^2}{4} * \rho\right) * \frac{1}{r^2} * g(\phi) \frac{kE}{N}$$

- The phase function represents the reflected light fraction to the observer:

$$g(\phi) = 10^{-0.01\phi}$$

- Some things of note:
  - Linear, monotonic SNR increase with exposure time (t_e)
  - Condensed linear inverse noise factor (N)
  - Phase function ($g(\phi)$) converges to 100% at ϕ = deg

The SNR Equation

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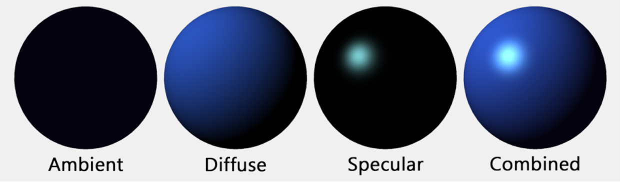
*Variables all described in paper

- A new phase function ($g_{diffuse}(\phi)$) of a diffuse, spherical object was substituted:

$$g_{diffuse}(\phi) = \frac{2}{3\pi^2}\left[\sin\phi + \left(\pi - \phi * \frac{\pi}{180°}\right)\cos\phi\right]$$



- A new noise formulation includes stray light, read noise w/time and multi-pixel smear due to motion:

$$N_{stray}(\psi, t_e) = 0.871 * d_{ap}^2 * t_e * e^{-2.8\psi}$$

$$N = \sqrt{P_{px}\eta + N_{dark}t_e + N_{read}^2 + N_{stray}^2} \;,\; n_{px} = \max\left(1, \frac{\alpha t_e}{\theta_{px}}\right)$$

$$P_{px} = P_{sun} * \frac{\pi d_{OS}^2}{4} * \rho * g(\phi) * \frac{1}{r^2} * \frac{\pi d_{ap}^2}{4} * \frac{1}{n_{px}} * t_e \;,\; \boxed{SNR = \frac{P_{px}*\eta}{N}}$$

Example Camera Suite

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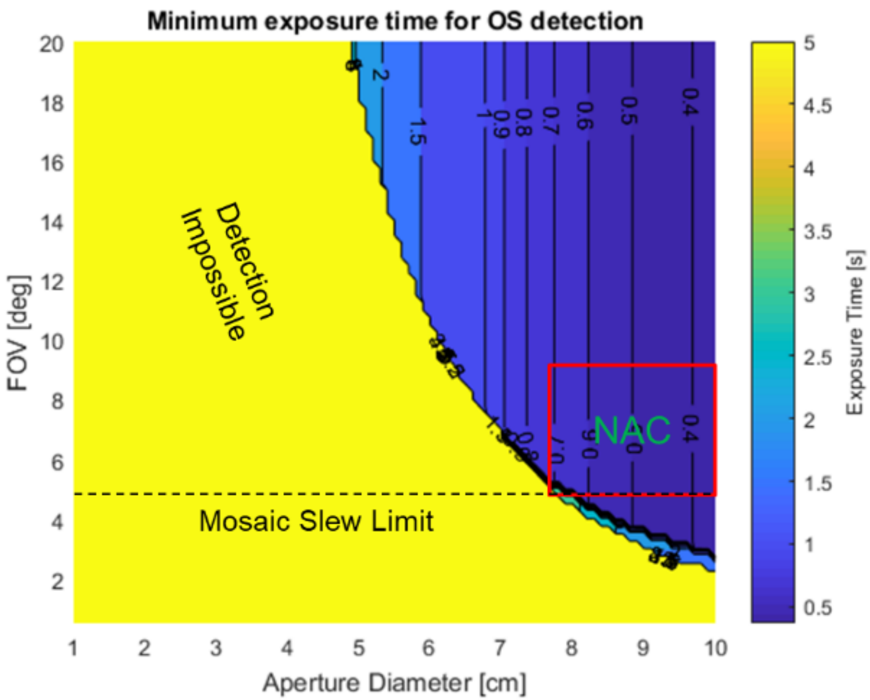
- An example set of camera electronics must be chosen to inform camera noise characteristics/efficiency.
- The example camera explored here was the Mars 2020 Enhanced Engineering Cameras (EECAMs) (Maki et al. 2016).
  - Common electronics for each camera w/ different optics
  - Existing technology, in production
  - Small, light, energy efficient electronics
- Requirements for each camera's optics, based on operational role and range regime:

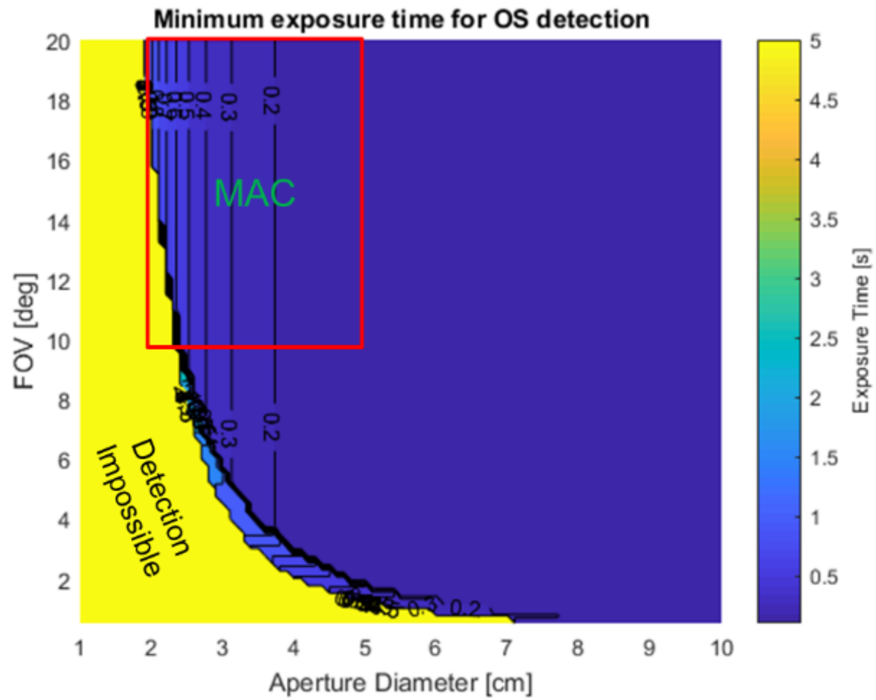
Sensor	Max Range	Min Range	FOV	Aperture	Accuracy of OS Centroid
NAC	>3,400 km	< 100 m	> 5°	< 10 cm	Angular: < 35 µrad
MAC	>1,000 km	< 10 m	> 10°	< 5 cm	Angular: < 500 µrad
WAC	>1 km	< 0.25 m	> 60°	< 5 cm	Angular: < 1 mrad Range: ~15 cm @ 10 m

Example Camera Suite

- Example camera optics chosen according to optimal and flexible performance in a tradespace analysis.
- Necessary exposure time to effect detection was examined as a function of aperture diameter and field-of-view (FOV), considering the previous requirements.



Detection results at 3,400 km range (maximum chord)



Redundant detection at 1,000 km range

Orbit & Dispersion Definitions

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- The SRO orbit is treated as nominal, according to the definition:

Element	Symbol	Value	Unit
Semi-Major Axis (SMA)	a	3,865.8	[km]
Eccentricity	e	0	[N/A]
Inclination	i	25	[deg]
Solar Beta Angle	β	~90	[deg]

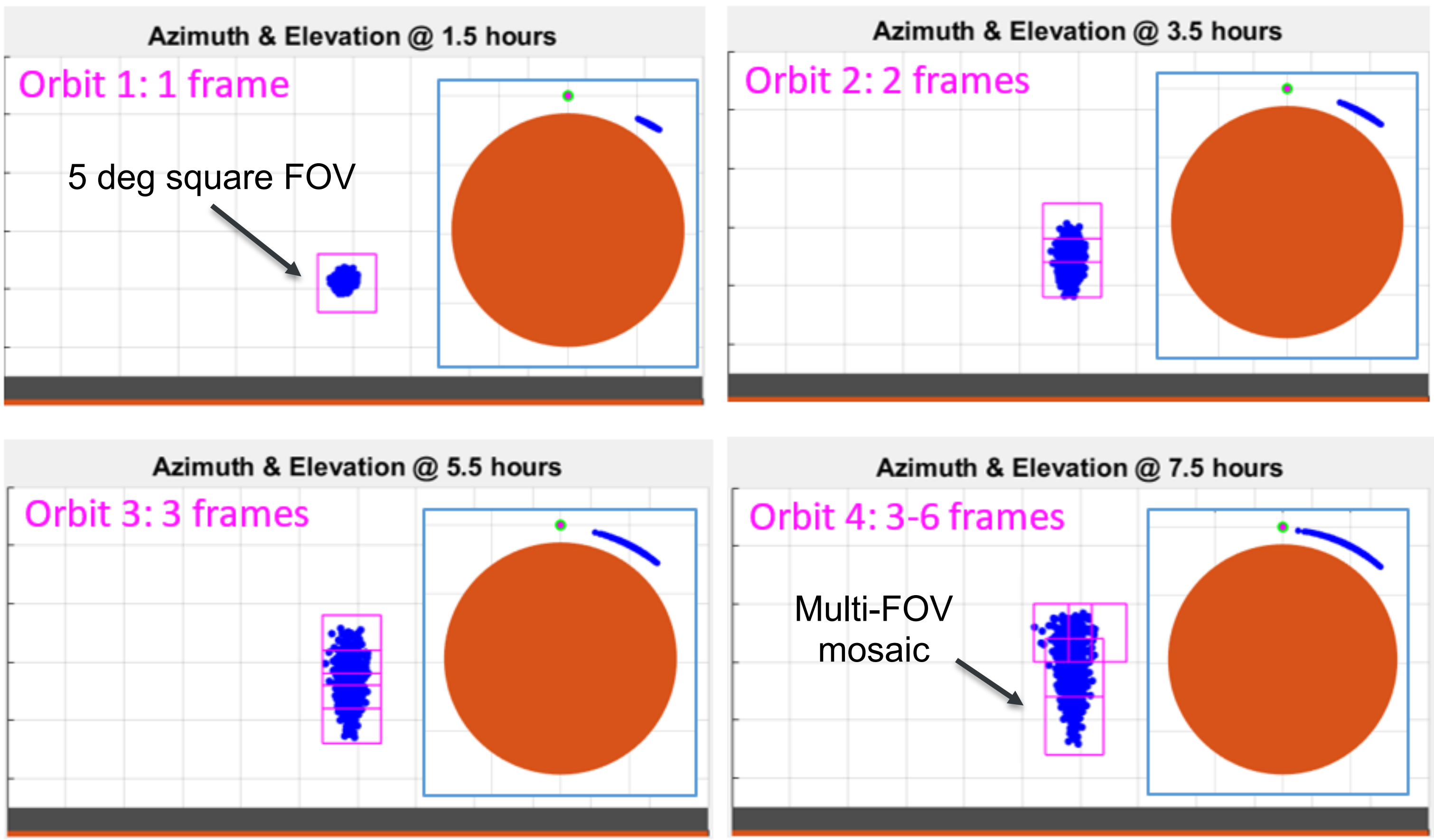
~470 km altitude

- Numerous (in this example case, 50) OS Monte Carlo instantiations are created, and distributed according to the notional MAV covariance dispersions (Benito et al. 2017):

Semi-Major Axis	Eccentricity	Apoapsis	Periapsis	inc	RAAN	Arg. of Latitude	Alongtrack
±32 km	< 0.019	-2 to +106 km	-97 to +2.4 km	±1.1°	±0.17 deg	±0.71 deg	±46 km

Orbital Dynamics

- This OS "cloud" disperses with time, adding a sense of urgency to the SRO's optical search and limiting minimum FOV to facilitate modest mosaicking.



Orbital Dynamics

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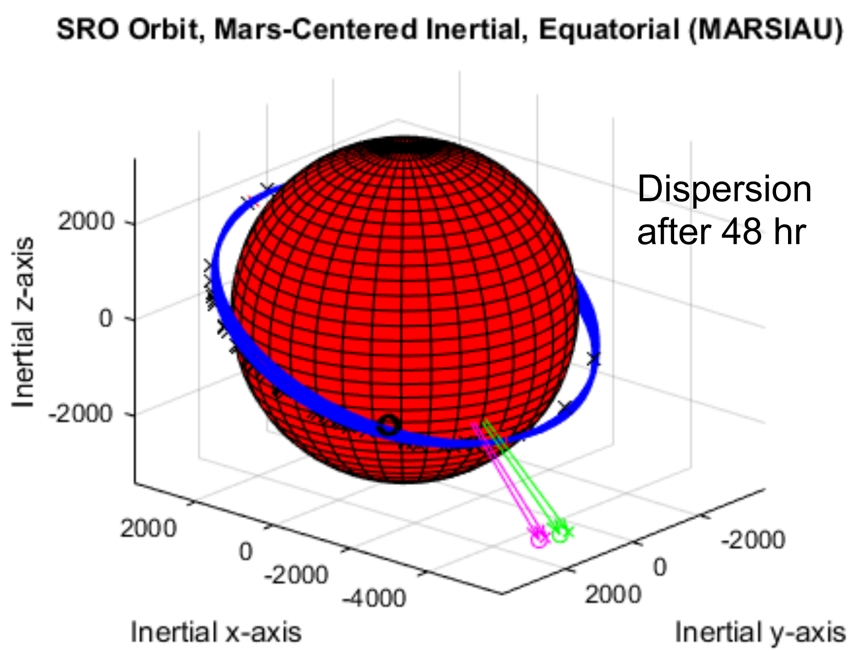
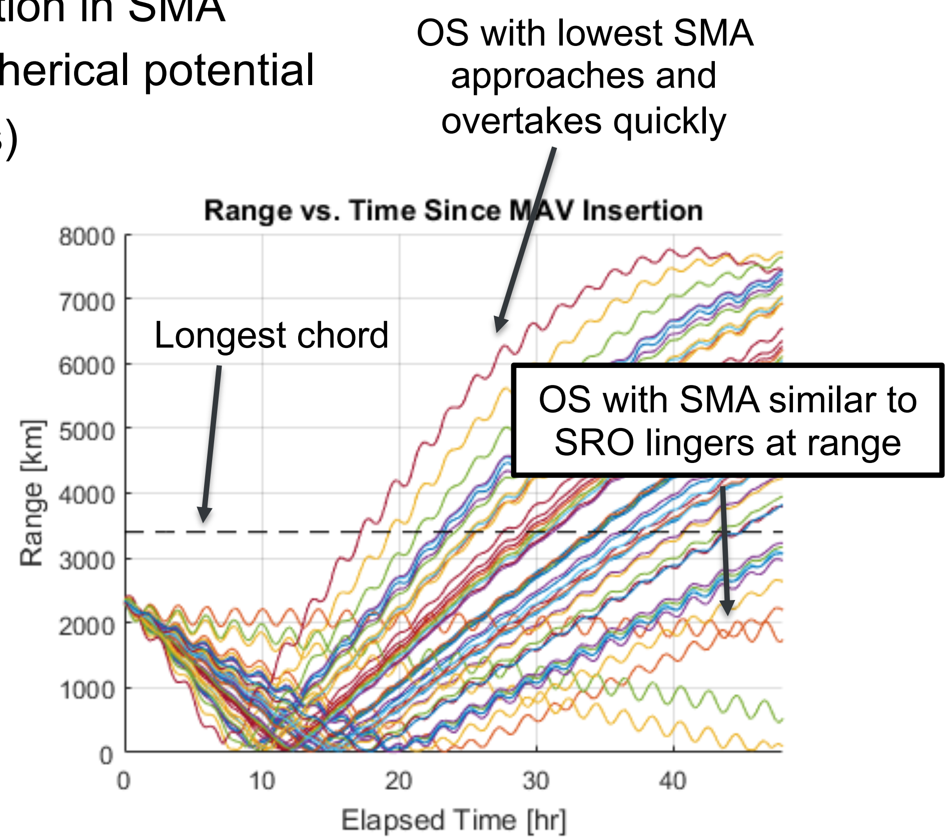
- Mars Orbiter Initial acquisition for Rendezvous Application (MOIRA) combines all of the previous effects w/orbital dynamics
- The OS "cloud" exhibits several expected behaviors:
  - Short-period relative (to SRO) motion
  - Mid-period divergence due to variation in SMA
  - Long-period divergence due to aspherical potential
  - (more on these behaviors in results)

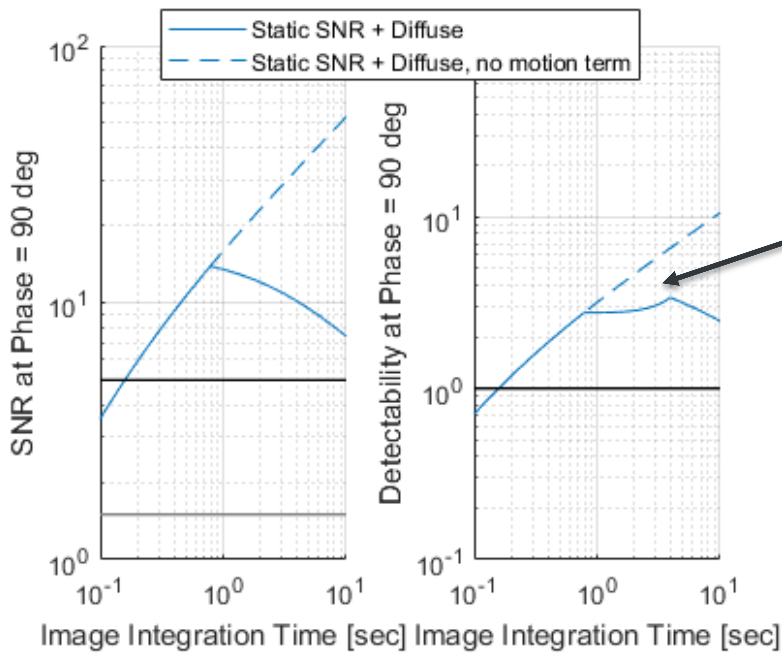




Radiometry in Orbital Dynamics

- A "detectability" metric was formulated to quantify the ease of detecting multiple lower-SNR adjacent pixels due to smear.

$$detectability = \begin{cases} n_{px} = 1 & SNR \ / \ 5 \\ 1 < n_{px} < 5 & SNR \ / \ (-0.5n_{px} + 5.5) \\ n_{px} \geq 5 & SNR \ / \ 3 \end{cases}$$



The "sweet spot", ~1 sec

Function of static SNR, motion, and camera noise vs. time

Initial Detection Results

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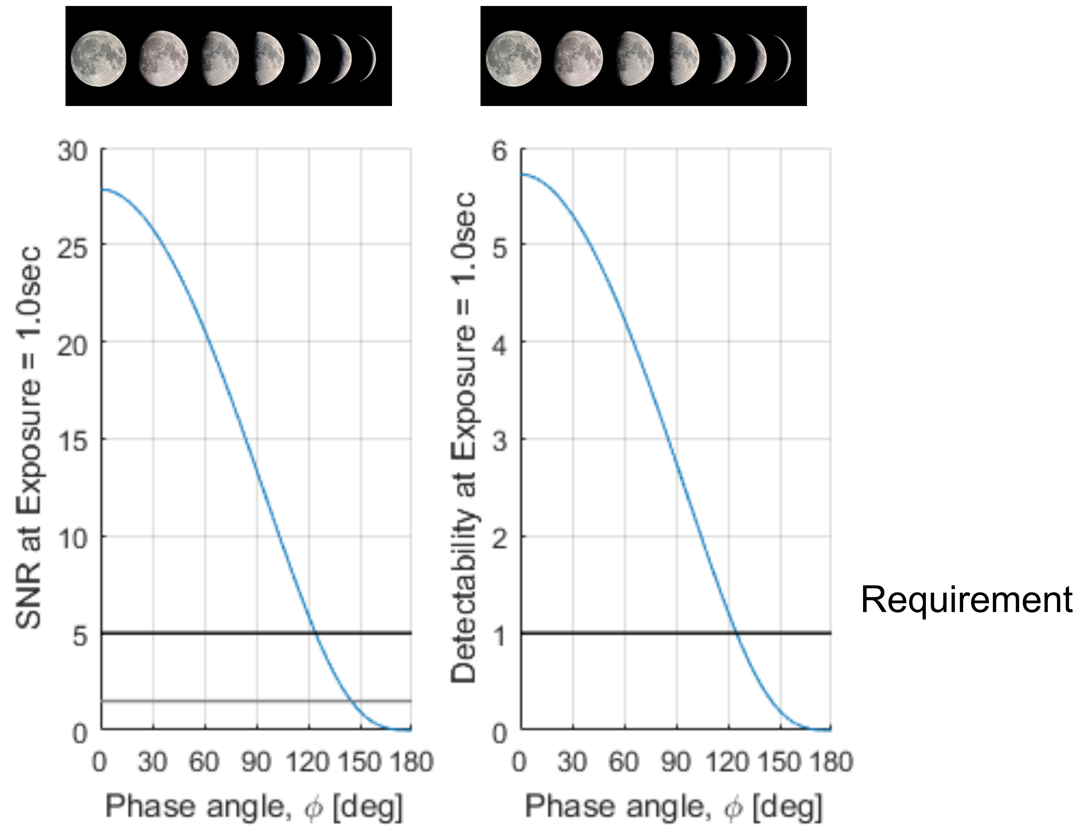
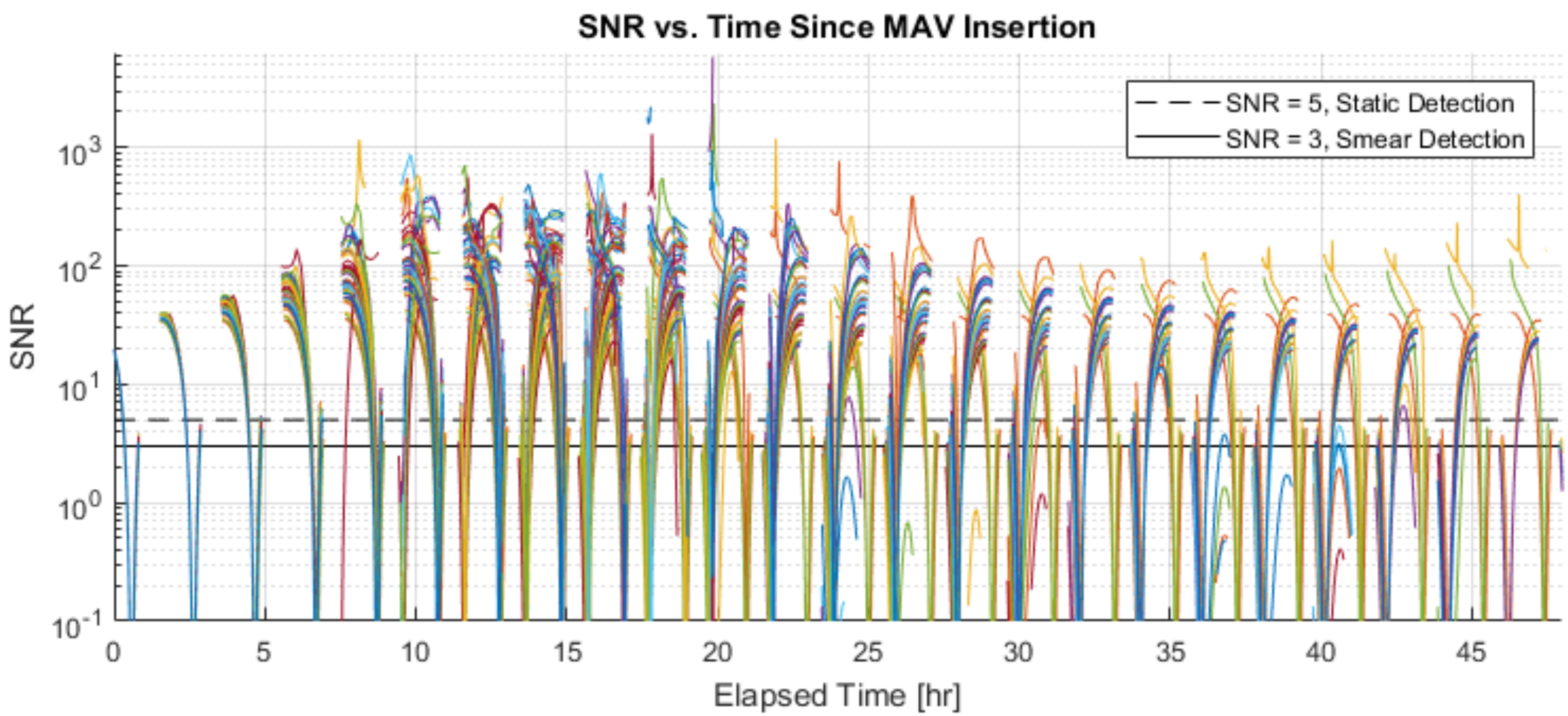
- The example camera suite NAC proves capable of effecting initial detection at OS insertion for more than half of the orbit (phase angle >= 90 deg “half-moon”)



Initial Detection Results

- The SNR of the individual OS candidates diverge significantly after ~8 hr, with the first candidate overtaking the SRO (below) and having its SNR drowned by martian backlight.
- Note eclipse behavior, divergence w/time, martian backlighting during overtake, and eventual occultation by the martian limb.



Relative Navigation Results

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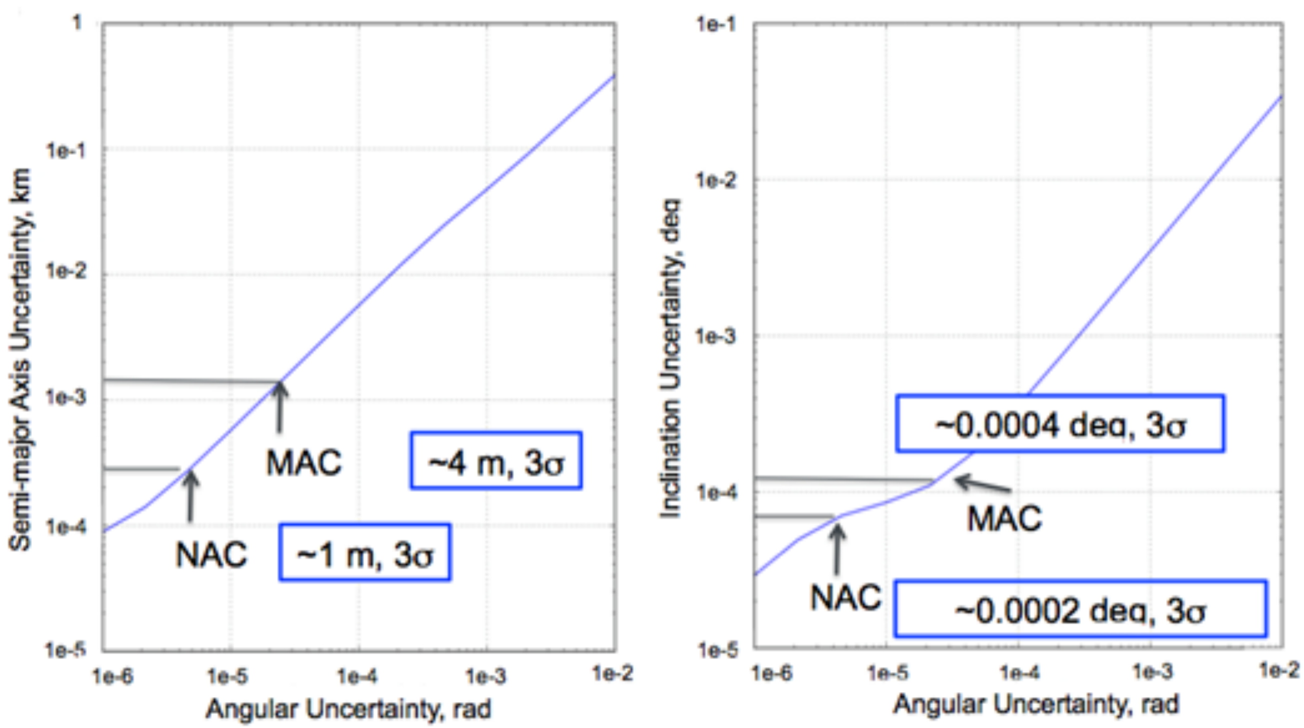
- Navigational uncertainties are sufficiently small at the end of the initial acquisition phase to begin formulating orbit matching maneuvers.
- The example camera suite provides capability for stereo and/or redundant tracking for the remaining phases of rendezvous.



Extension to Terminal Phase

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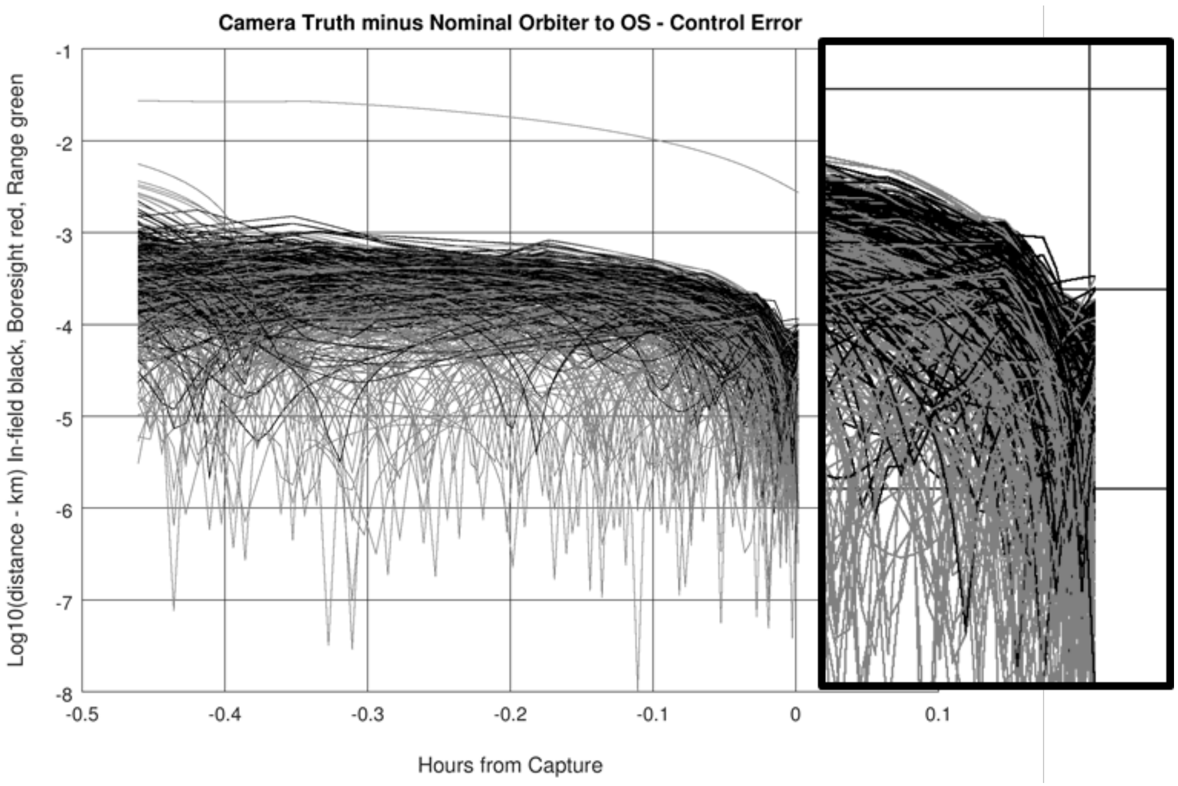
- Camera sufficiency extends to later phases of the rendezvous operation, effecting a safe and accurate rendezvous and capture with the OS.
- Subject to further investigation and/or publication.



Conclusion

- Results show that optical detection of an object in Mars orbit by a robotic orbiter is feasible, with the following features:
  – Passive optical system measures reflected solar visible light
  – No need for RF crosslink, radar or LIDAR
  – The OS can be passive, inert, and non-cooperative
  – The camera requirements are achievable with current technology
  – The example cameras are compatible with all phases of rendezvous, with custom optics for each of the three camera types
  – The navigation uncertainties achieved are suitable to begin formulating orbit matching maneuvers

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This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. Government sponsorship acknowledged.